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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
12 September 1995

3. REPORT TYPE AND DATES COVERED
Final 1 Jul 92 - 30 Jun 95

4. TITLE AND SUBTITLE
Compact, high-power two-photon lasers

5. FUNDING NUMBERS
DAAL03-94-G-0174

6. AUTHOR(S)
Daniel J. Gauthier

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Duke University
Department of Physics, Box 90305
Durham, NC 27708-0305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 30572.10-PH-YIP

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The development of two-photon lasers and techniques for controlling chaos in fast dynamical systems is described.

14. SUBJECT TERMS
two-photon laser, chaos, controlling chaos

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

COMPACT, HIGH-POWER TWO-PHOTON LASERS

Final Report

Daniel J. Gauthier

Research Period Covered by Report:
1 JUL 92 - 30 JUN 95

U. S. Army Research Office

Grant Number DAAL03-92-G-0286

Duke University, Department of Physics
Box 90305, Durham, North Carolina 27708

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3. The Two-Photon Laser

3.1. Statement of the problem

The primary goal of our program is to develop and characterize a fundamentally new type of quantum oscillator that is based on the two-photon stimulated emission process: the two-photon laser. We are motivated to investigate two-photon lasers because of the expectation that the laser will have distinct and potentially useful operating characteristics in comparison to normal one-photon lasers. For example, researchers envisioned in the early 1960's [1] that the two-photon laser would be an 'ideal' laser source since it can generate two tunable frequencies, operate at high power, and store large energies (recall that there were only fixed-frequency, modest power lasers in the early sixties). While the need of a laser that meets these specifications is diminished by the advent of numerous one-photon laser sources, we are still intrigued by the two-photon laser because it challenges our understanding of the interaction of light with matter. It is a highly nonlinear, far from equilibrium system that cannot be analyzed using standard perturbation techniques and it is expected to display novel quantum optical effects. For example, it is predicted to display unique threshold behavior, bistability [2], and squeezing [3]. Unfortunately, the practical benefits of the laser have not been realized nor have the theories been tested because it has been difficult to achieve two-photon lasing due to the lack of suitable gain media. The section on Two-Photon Laser Development describes our progress on the realization of this novel quantum oscillator.

During the course of this work our emphasis evolved from two-photon laser development to controlling chaos in fast dynamical systems. Our motivation for moving into this new research area is that: it may result in important technological advances; we are the only experimental group considering schemes for controlling chaos in fast dynamical system, such as optical systems; we can contribute significantly to the field in a short period of time; and the control algorithms can be used to stabilize the fast-time-scale instabilities that are predicted to occur in two-photon lasers. One important characteristic of controlling chaos schemes is that it is possible to render a chaotic system periodic or stable by applying only small perturbations to some accessible system parameter [4]. The section on Controlling Chaos in Fast Dynamical Systems describes our progress in this area.

3.2. Summary of Important Results

3.2.1. Two-Photon Laser Development

In the first phase of our research program on two-photon lasers we devoted our time to developing a simple understanding of the microscopic origins of the two-photon gain process and the competing nonlinear optical effects that hinder the lasing process [5]. Based on this research, we devised a new gain medium that is based on the two-photon Raman scattering process. We are continuing to optimize the gain medium and our preliminary results [6] are very encouraging: we have amplified an intense beam of light by ~30% which is ~300 times larger than previously reported two-photon gain media [7]. The enhancement is due to the relative insensitivity of the gain process to broadening mechanisms allowing us to use a high-density atomic vapor.

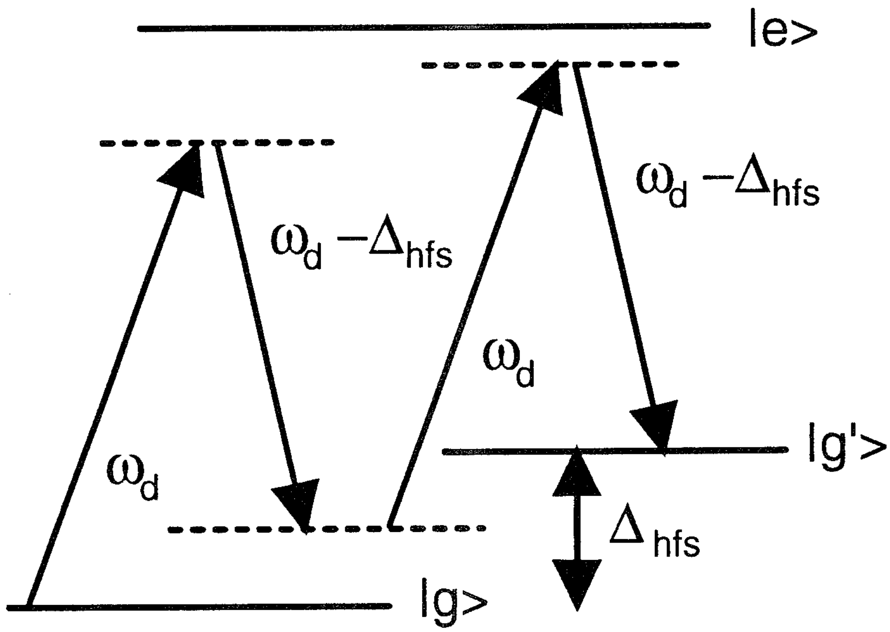

Figure 3.1: The two-photon Raman scattering process. The probe beam (frequency $\omega_d - \Delta_{hfs}$) is amplfied at the expense of the pump beam (frequency ω_d) at the atom make the transition $|g> \rightarrow |g'>$.

The new gain medium is based on the two-photon Raman scattering process shown diagrammatically in Fig. 3.1. It has relatively strong, near resonantly enhanced, degenerate two-photon transitions that occur at a frequency $\omega_{2\gamma} = \omega_d - \Delta_{hfs}/2$, where ω_d denotes the pump laser frequency and Δ_{hfs} denotes the frequency splitting of the lower states. The two-photon gain feature is spectrally removed from the one-photon gain that occurs at frequency $\omega_{1\gamma} = \omega_d - \Delta_{hfs}$ in the same system and hence the two-photon gain can be selectively enhanced by a high-finesse optical resonator. These characteristics are similar to those of the dressed-atom gain medium that was used to realize the first continuous-wave two-photon optical laser [7]. In addition, the two-photon Raman gain medium is relatively unaffected by inhomogeneous broadening due to spatial variation in the pump beam intensity nor the Doppler effect. Hence, spectrally narrow-band two-photon gain features can be observed in a atomic vapor cell where large atomic number densities can be produced easily.

Large two-photon amplification is observed in a laser-pumped potassium vapor (length 7.5 cm, vapor pressure $\sim 5.5\times10^{-4}$ torr). The pump laser (frequency ω_P), an 850 mW actively stabilized Ti:sapphire laser, is linearly polarized, has a ~1 mm beam spot size as it passes through the vapor cell, and is tuned ~800 MHz below the 770-nm $4S_{1/2}$ $(F = 1) \rightarrow$ $4P_{1/2}$ $(F = 1)$ ^{39}K transition. The pump laser serves two purposes: it creates the necessary inversion between the ground-state hyperfine levels (splitting Δ_{hfs} =462 MHz) by optically pumping atoms from the $F = 2 \rightarrow F = 1$ levels as they move into the pump beam; and it acts as the pump field for the two-photon Raman process. The probe laser (frequency

ω_R), a grating stabilized diode laser, is polarized orthogonal to the pump laser, crosses the pump laser at a ~12 mrad angle, and has a ~ 500 μm beam spot size. Significantly smaller crossing angles (<6 mrad) could not be used due to the appearance of four-wave mixing processes. We observe large (>5,000%) amplification of the probe laser due to one-photon Raman scattering when $\omega_R \approx \omega_P - \Delta_{hfs}$ and its power is low (<10 μW). For higher powers (~10 mW), the one-photon Raman gain decreases dramatically and a new gain feature appears as seen in the Fig. 3.2. We attribute this probe-dependent feature to the two-photon Raman scattering process. The probe beam is amplified by ~ 30% which should be sufficient to observe two-photon lasing.

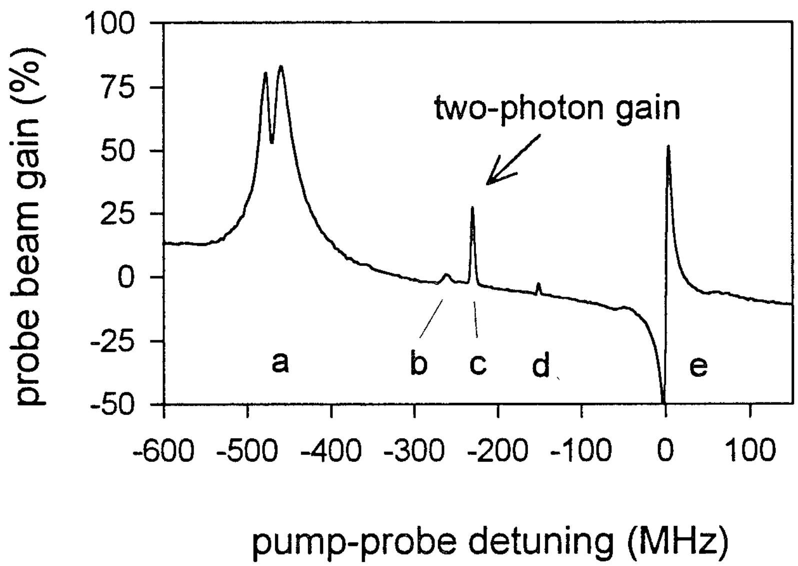

Figure 3.2: Pump-probe spectrum of laser driven potassium atoms. The narrow gain feature (c) is attributed to the two-photon Raman process.

The future goals of this program are: to suppress the competing nonlinear optical processes that occur simultaneously in the same system (weak self-focusing and one-photon dressed-atom gain) using a nitrogen or helium buffer gas; and the realization of a two-photon laser using the new gain medium. This work will be supported by the U.S. Army Research Office through the ASSERT Program and the National Science Foundation through its Young Investigator Program.

3.2.2. Controlling Chaos in Fast Dynamical Systems

During the last year-and-a-half we have made significant advances in developing a scheme for controlling chaos in fast dynamical systems [8] that is an alternative implementation of

the original Ott-Grebogi-Yorke idea [4]. It employs continuous feedback, does not require rapid switching or sampling, nor does it require a reference signal corresponding to the desired orbit. We have used it to stabilize highly-unstable periodic orbits in a chaotic electronic circuit where the time-scale for the fluctuations is under 100 nsec as described in the 1994 'Research Highlights of the ARO Physics Division.'

Stabilization of UPO's is achieved by continuous adjustment of an available system parameter by a feedback signal

$$\epsilon(t) = \vec{\gamma}_f \cdot [\vec{\xi}(t) - (1-R)\sum_{k=1}^{\infty} R^{k-1}\vec{\xi}(t-k\tau)] \quad , \tag{3.1}$$

that is proportional to the difference between the present value of an accessible state variable $\vec{\xi}(t)$ and an infinite series of values of the state variable delayed by integral multiples of the period of the orbit τ, where $0 \leq R \leq 1$, and $\vec{\gamma}_f$ is a gain vector. We refer to this control scheme as 'extended time-delay auto-synchronization' (ETDAS). Note that the form of Eq. 3.1 is closely related to the amplitude of light reflected from a Fabry-Pérot interferometer suggesting an all-optical implementation. The case $R = 0$ corresponds to the scheme investigated theoretically by Pyragas [9] and Lu and Harrison [10], and experimentally by Bielawski *et al.* [11], Pyragas and Tamesevicius [12], and our group. The more general scheme ($R \neq 0$) can stabilize highly unstable orbits and it is capable of extending the domain of effective control significantly. We emphasize that, for any R, $\epsilon(t)$ vanishes when the system is on the UPO since $\vec{\xi}(t-k\tau) = \vec{\xi}(t)$ for all k. Thus, whenever ETDAS is successful *there is no power dissipated in the feedback loop.*

We have used ETDAS to stabilize the UPO's of a high-speed diode resonator driven at 10.1 MHz (corresponding to a drive period under 100 nsec) using analog circuitry to generate the necessary feedback signal (Eq. 3.1) as shown in Fig. 3.3. We are in the process of performing a careful comparison between our experimental results and the predictions of the theory [13] recently developed by Prof. Socolar's group at Duke.

A natural extension of this work is to apply ETDAS to a high-speed chaotic optical system such as a diode laser (the original motivation for the development of ETDAS). Understanding how to control the dynamics of chaotic diode lasers has practical implications because the performance of many commercial devices that use them (e.g., compact disc players) is limited by feedback-induced chaotic instabilities. Controlling the dynamics of diode lasers using electronic and all-optical implementations of ETDAS is one of the main goals of our program on the 'Experimental Control of Chaos' recently supported by the U.S. Army Research Office.

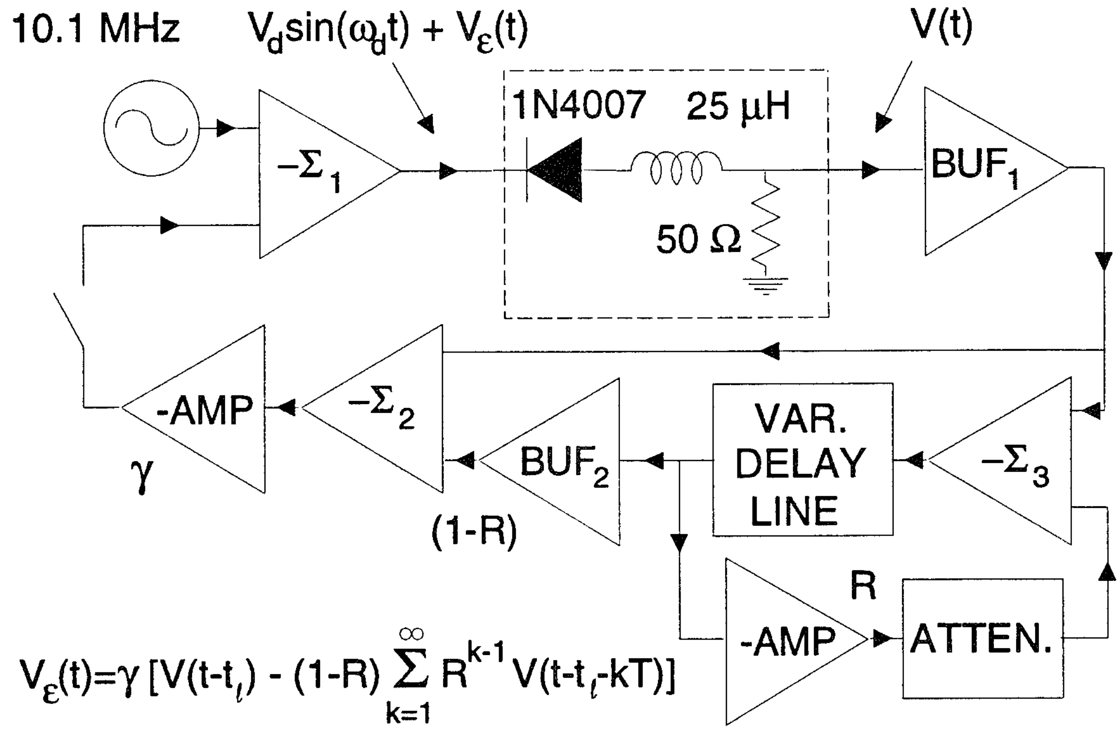

Figure 3.3: Analog implementation ETDAS used to control a diode resonator. Components: high-impedance buffers (BUF), inverting op amp (-AMP), inverting, summing op amp (-Σ), attenuator (ATTEN.), and low-loss variable delay line. The time lag t_ℓ between BUF_1 and -Σ_1 was ~10 nsec.

3.3. List of publications and technical reports

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3.4. List of participating personnel

Ms. Hope Concannon (Research Assistant), Dr. Daniel Gauthier (Assistant Professor), and Mr. David Sukow participated in this research program and were partially supported by the grant. Both Ms. Concannon and Mr. Sukow received a Master's degree in Physics during the course of this program.

4. Inventions

D.J. Gauthier and H.G. Robinson, 'Compact enhanced performance optical isolator using a Faraday rotator,' U.S. Patent filed 9 NOV 94.

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